TECHNICAL NOTES.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 71.

EXPERIMENTS WITH SLOTTED WINGS.

Translated from
"Zeitschrift für Flugtechnik und Motorluftschiffahrt,"
June 15, 1921,
By the National Advisory Committee for Aeronautics.

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Slotted Wing Sections,

By C. Lachmann of Darmstadt.

Introduction.

The idea of increasing the lift of an aerofoil by subdividing it goes back to gliding flight experiments by the writer before the war. A crash in August, 1917, with a Rumpler C airplane, on account of stalling, caused the idea to be put into concrete form and presented for a patent in 1918. The patent claim reads: "Supporting surface characterized by its being divided into a number of tandem components which together form a wing section." The application was at first rejected because the patent office did not believe in the possibility of increasing the lift by dividing the wing. The issuing of the patent was made dependent on conclusive proof of such increase.

Already in 1917, a small wooden model of a divided wing was made in the laboratory of the school for observers in Cologne (Fig. 1). This model was expected to show the effect of the slots on the air current, with the aid of a smoke blast. The rather primitive experiments gave however no noteworthy results, chiefly because the slots were too narrow.

Further experiments were rendered impossible by my war service as airplane pilot and subsequent severe wounding, and by intensive professional work after the war.

The announcement of the practical experiments of Handley-Page in 1920, with a divided wing section, gave occasion for calling the attention of the professional world and the patent office to the German priority of the idea. The principal proof lay in the two models made according to the instructions of the writer and tested in the wind tunnel of the aerodynamic institute at Göttingen. The results of these experiments are here given. Attention should first be called to the fact, however, that the results obtained do not yet represent the practically attainable optimum, since the arrangement of the slots was only tentative, without theoretical considerations, and with the closest possible adherence to the patent drawing. Any analytical investigation of the air current appears extremely complicated. The increase in the lift values of the divided wing surely bears some relation to the changes in the air current, since the diversion of the stream lines from the suction side of the section and the formation of a "dead-water region" occur at larger angles of attack than in the case of the closed wing section.

For showing the effect on the current, a three-part wing section was tested in the hydraulic laboratory of the Darmstadt Technical High School. The black walnut model was 40 x 25 cm., and was installed at an angle of attack of about 40° in the 40 cm. wide conduit, which was inclosed on one side by a thick glass plate. The average velocity of the water was 1 meter per second. The course of the stream lines could be recognized by the air bubbles in the water and could be made still plainer by admitting a solution of uranine through a small pipe. When the slots were open, the streamlines ran parallel to the curve of the suction side. When the slots were closed, there was a visible loosening of the streamlines on the upper side of the wing section. The course of the variable layer and the formation of the turbulent dead-water region showed very plainly, when a strip of linen loosely covering the upper side, was attached to the leading edge. The loosening of the streamlines from the suction side and the formation of the dead-water region also took place with the slots open, when the velocity of the water was raised to 4 meters per second. These experiments are not yet finished and the stream pictures thus far obtained can not pass for absolutely correct representations.

Significance of Form and Number of Slots.

Wing section No. 422 was chosen as the basic section for subdivision in the Göttingen experiments. In Figs. 2 and 3 are given the polar diagrams derived from the results of the measurements. For comparison, the polar curves of the basic section are given on both diagrams. Model L-2 corresponds to model L-1, even to the sharp edges of the outlet openings on the suction side. This was simply for exact conformity of the experiment model with the drawing of the patent.

As may be seen from the diagrams, the result of the division is a maximum lift increase of about 60% for angles of attack which are about twice aslarge as for closed wing sections. Fig. 4 shows that a decrease of the lift-drag ratio occurs with divided wing sections. Curves 422' and L_2' were obtained for a complete airplane on the basis of an average fuselage drag $C_W = 0.03$.

Wing section L_2 gives an astonishing improvement of the lift-drag ratio, with only a small loss in the maximum lift value. Especially for small angles of attack there is a noteworthy reduction in the wing section drag. This phenomenon is probably connected with the more uniform shape of the slots of section L_2, for which (in common with the continuity condition), the increase of the velocity of the current takes place in a more harmonious manner than for section L_1. We learn from this that in actual construction, the continuity of path of the acceleration, aside from the centrifugal accelerations, which are grasped with difficulty, is best tested graphically.

From the curve diagrams of the Göttingen measurements for single-slotted wings, it is evident that, with the upper outlet completely closed, the wing-section drag, within certain small angles of attack, is nearly equal to the drag of a closed section. The irregular shape of the pressure side accordingly plays no role with these small angles of attack, which is important in the construction of slot-closing devices.

The shapes of the individual parts of the wing section, L_1 and L_2, are still very unfavorable. In particular, these parts are too thick in proportion to the chord. The width of the slots also seems to be too narrow. The Göttingen curves for single-slotted wing sections give an idea of the importance of more favorable shapes for the slots and parts of the wing section.

The differences of the experimental results so far obtained between wing sections with only one slot and those having two or more may be summarized as follows:

1. Wing sections with two or more slots give greater lift values than those with only one slot;

2. The course of the polar curves is continuous for wing sections with two or more slots, while for sections with only one slot a sudden increase of the C_w values occurs in the region of small angles of attack;

3. The pressure center varies more for large anglesof attack in sections with two or more slots than in sections with only one slot.

The question of the significance of the angle of setting of the part sections to the chord of the total wing section and the relation between the width of the slots and the velocity of the fluid flowing through them require further experimental elucidation.

A.

Influence of Slots on Power Absorption and Speed in Horizontal Flight.

For exhibiting this influence, a transformation of the known equations for the lift and the coordinated power absorption was undertaken, in order to represent the weight per HP, G/N, as a function of the horizontal speed.

It is:

$$\frac{75 \times N_i \times \eta}{v} = C_w \times F \times \frac{\gamma}{2\,g} \times v^2,$$

or

$$\frac{N_i}{F} = C_w \times \frac{\gamma}{2\,g} \times \frac{1}{75 \times \eta} \times v^3 = C_w \times \psi \times v^3 \quad \ldots\ldots \quad (1)$$

whereby

$$\psi = \frac{\gamma}{2\,g \times 75 \times \eta}$$

from

$$A = G = F \times \frac{\gamma}{2\,g} \times C_a \times v^2$$

follows

$$v = \frac{1}{C_a^{1/2}} \sqrt{\frac{G}{F} \times \frac{1}{\frac{\gamma}{2\,g}}}$$

or

$$v = \frac{1}{C_a^{1/2}} \times 4 \sqrt{\frac{G}{F}} \quad \ldots\ldots\ldots\ldots \quad (2)$$

if we adopt $\frac{\gamma}{g} \sim \frac{1}{8}$.

By the substitution of this expression for v in equation 1, we obtain for the weight per horsepower

$$\frac{G}{N_i} = \frac{C_a^{3/2}}{C_w} \times \frac{75 \times \eta}{4} \times \frac{1}{\sqrt{\frac{G}{F}}}$$

By squaring we obtain

$$\left(\frac{G}{N_i}\right)^2 \times \left(\frac{G}{F}\right)^2 = \frac{C_a{}^3}{C_w{}^2}\left(\frac{75 \times \eta}{4}\right)^2 \quad . \; . \; . \; . \; . \; . \; . \qquad (3)$$

Or, stated in words: The product of the wing loading by the weight per horsepower is proportional to $\frac{C_a{}^3}{C_w{}^2}$ The change of η proportional to v is hereby neglected.* To equation (3) corresponds the known equation from the propeller theory

$$\left(\frac{P_o}{L_o}\right)^2 \left(\frac{P_o}{F_o}\right)^2 = 2\,\frac{\gamma}{g}\,,$$

or, in words: The product of the surface utilization and the square of the power utilization is constant.

If $\eta = 0.7$, then

$$\frac{G}{N_i} = \frac{C_a{}^{3/2}}{C_w}\;\frac{13}{\sqrt{\frac{G}{F}}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (3a)$$

The value $\frac{C_a{}^{3/2}}{C_w}$ might be designated as coefficient of weight per horsepower and $\frac{1}{C_a{}^{1/2}}$ as speed coefficient of weight per horsepower. In Fig. 5 the weight per horsepower is represented as a function of the speed for sections 422, L_1 and L_2. Curves 422' and L_2' were thus produced by employing for the denominator of the expression $\frac{C_a{}^{3/2}}{C_w}$ a mean fuselage drag ($C_w = 0.03$). From the

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*According to Bendemann

$$\eta = v \times \xi \sqrt[3]{\frac{1 - \frac{\eta}{\xi}\quad F \times \gamma}{370 \times N}}$$

is the propeller efficiency (Z. für F. u. M., 1918).

graphic representation the following result is obtained:

I.

Without Reference to the Fuselage Drag.

By the increase of the speed beyond the point of intersection of the curves 422 and L_2, the maximum weight per horsepower of the closed wing section exceeds that of the divided section by about 23%. The speed coefficient for the maximum per horsepower of the closed section is thereby 48% greater than that of the divided wing section. If we take the product

$$G\ v = T \text{ (Transportation economy)},$$

then the closed section surpasses the divided one by 82%.

II.

With Reference to a Mean Fuselage Drag.

The above considerations are of pure theoretical significance, since in practice we always have to reckon with a fuselage drag and can only fly with regard to safety and not to the maximum weight per horsepower. By the introduction of a mean fuselage drag, the matter assumes an entirely different aspect. The maximum value of the weight per horsepower now exceeds, for the divided section L_2, the maximum value of section 422 by about 6%. For reasons already known, this value is not practically attainable. If, however, the maximum value a' of the closed section is chosen for the divided section, then in the case of the divided section there is the possibility of coming within 9.3% of the highest speed with constant weight per horsepower.

The divided section accordingly works more favorably than the closed section for high weights per horsepower, high wing loading and relatively low speeds. Since the speed in horizontal flight also increases in proportion to the wing loading, the influence of the slots on the horizontal speed must be determined before applying the rule to a practical example.

III.

Alteration of the Flight Speed by Means of the Slots.

The previous considerations apply to divided wing sections without closing devices. It is evident that the application of such a device would serve the purpose of combining the advantages of both kinds of sections. With constant weight per horsepower, a decrease in the speed can be effected by opening the slots. The minimum attainable speed, which is of especial importance for the length of the run in taking off and in landing is cut off on the axis of the abscissas by the vertical tangent to the curve of the weight per horsepower. In the foregoing case, a speed decrease of about 20% is possible.

B.

Influence of Slots on Horizontal Speed.

The horizontal speed is given by

$$v_g = \frac{C}{\rho^{1/2}} \qquad (4)$$

$$\frac{1}{\rho^{1/2}}$$

is the speed coefficient of gliding flight.

$$C = \sqrt{\frac{2g \times g}{F \times \gamma}}$$

and

$$\rho = \sqrt{C_a^2 + C_w^2}$$

the length of the radius vector.

With reference to a mean fuselage drag of $C_w = 0.03$, we have the following representation for the three main forms of gliding flight.

Section	Inclination of flight path	Angle of attack	$\left(\frac{1}{\rho^{1/2}}\right)$min.
422	6° 10'	+1.2°	1.20
L-1	7° 30'	+8.6°	0.96
	Decrease 20%		
	a) Swiftest gliding flight.		
422	14° 50'	-5.8°	2.26
L-1	43° 20'	-4°	3.02
	Acceleration = $33\frac{1}{3}$%		
	b) Vertical diving.		
422	90°	-10°	3.16
L-1	90°	- 5.2°	3.44

Acceleration = 8.9%.

The significance of diminishing the gliding speed for the economy of flight, is best illustrated by a practical example.

The following data are taken as the basis:

Total weight of airplane	$G = 650$ kg.
Normal engine power on ground	$N = 115$ HP
Area of supporting surfaces	$F = 15.1$ sq.m.
Weight per HP	$G/N = 5.65$ kg.
Wing loading (kg/sq.m.)	$G/F = 43$ kg.
Propeller efficiency	$\eta = 0.7$

We shall investigate three cases:

Case 1. The airplane has the normal wing section 422.

a) From formula 3a we obtain for the coefficient of the weight, per HP, 5.65,

$$\frac{C_a^{3/2}}{C_w} = 2.34$$

The coordinate maximum speed according to formula (2) is

$$v_{max} = 180 \text{ km/h}.$$

The product $T = G \times v$ hereby attains the value

$$T = 116,900 \text{ kg} \times \text{km/h}.$$

The speed for the flattest gliding flight is, according to equation (4) for $\gamma = \gamma_0 = 1.244$

b) With double the wing loading, the following values are obtained

$$G/N = 13.3 \text{ kg/HP}$$

$$G/F = 86 \text{ kg/sq.m.}$$

The coefficient of weight per HP is then

$$\frac{C_a^{3/2}}{C_w} \sim 8$$

From diagram No. 8, it follows that for these values, both wing sections are about equally justified in the region between the critical and the maximum speed. With this weight per HP, we have

$$v_{max} = 43 \text{ m/s} = 155 \text{ km/h}.$$

The gliding speed is raised however to

$$v_{g\,min} = 44.1 \text{ m/s}$$

such a speed in the flattest gliding flight being naturally excluded in practice.

Case 2.

a) The airplane has slots without closing device. We will again assume that

$$G/N = 11.3 \text{ kg/HP} \quad \text{and} \quad G/F = 86 \text{ kg/sq.m.}$$

The attainable speed is then

$$v_{max} = 35 \text{ m/s} = 125 \text{ km/h}.$$

and

$$T = 162{,}500 \text{ kg} \times \text{km/h},$$

or about 39% more than in Case 1a.

$$v_{g\,min} = 35.4 \text{ m/s}$$

and the wing loading for the undivided section is raised to

$$G/F = 67 \text{ kg/sq.m.}$$

and the weight per HP to

$$G/N = 8.25 \text{ kg/HP}.$$

The corresponding coefficient of the weight per HP is 5.2. The speed coefficient is 1.29, corresponding to

$$v_{max} = 42 \text{ m/s} = 151 \text{ km/h. and}$$

$$T = 152{,}500 \text{ kg} \times \text{km/h}.$$

In comparison with Case 1 there is therefore an increase of about 30% in transportation economy. The divided wing is accordingly adapted, even without slot-closing device, for increasing the flight economy.

The critical speed, in this case, lies at

$$v_{min}\ 23.4 \text{ m/s} = 84.5 \text{ km/h}.$$

Hence the difference between the speed limits is quite large.

Case 3. The conditions are assumed to be the same as in the foregoing case. The divided wing section is however provided with a closing device, by means of which it is assumed that the same conditions can be attained as in a completely closed wing section. We then have

$$v_g = 31.4 \text{ m/s}$$

$$v_{max} = 180 \text{ km/h}$$

$$T = 182{,}000 \text{ kg} \times \text{km/h}$$

or 56% more than in Case 1a.

C.

Influence on Ceiling, Climbing Speed and Controllability.

The ceiling z_g of an airplane, according to Kann, is

$$z_g = 1280 \log \left[358 \frac{\left(\frac{C_a{}^3}{C_W{}^2}\right)_{max} \eta^2}{\left(\frac{G}{n_o}\right)^2 \times \left(\frac{G}{F}\right)} \right]$$

When the weight per HP, wing loading, propeller efficiency and fuselage drag are given, only the value $(C_a^3/C_w^2)_{max}$ plays a decisive role. In diagram 6, this value is given as a function of the angle of attack. The curves 423' and L 2' were obtained with reference to a mean fuselage drag, while the remaining curves show the course of the values for the wings alone. In practice there is a consequent superiority of the divided wing section with reference to the attainable ceiling and therewith also the climbing speed, since all factors which increase the height limit also decrease the climbing time.

The radius of the narrowest possible curve can, in practice, be made equal to the radius of the curve which is flown with the angle of attack for the height limit. The radius of the practically narrowest possible curve is therefore

$$r_{min} \frac{v^2}{g\sqrt{\left(\frac{\gamma_o}{\gamma_g}\right)^2 - 1}}$$

The divided wing section is also superior to the closed with reference to controllability.

D.

Significance for Longitudinal Stability.

The danger of stalling is less with a divided wing section. It is therefore especially adapted for school airplanes, because mistakes in steering will be more evident to the pupil than formerly, on account of the greater angle of attack. This perhaps offers a means for reducing the principal source of danger in learning to fly.

As a slot-closing device, some such arrangement as the following is possible. A mass is connected with the lever which operates the closing device, with the interposition of springs of suitable strength, in such a way that in the event of a sudden dangerous slackening of the airplane speed, it is carried forward by its inertia and opens the slots.

Or a divided surface may be arranged as a horizontal damping wing while the main wing is provided with fewer slots or not any at all (Fig. 7). If the engine stalls, on the one hand, the lift of the damping wing increases relatively more than the lift of the main wings and, on the other hand, the center of pressure of the damping plane moves back more, thereby producing a backward turning moment. Equilibrium is obtained when the sum of all the moments and of all vertical and horizontal components is zero, that is, when

$$L \times l + D \times d - F \times f = 0$$

$$S + \vec{L} + \vec{D} + \vec{F} = 0$$

E.

<u>Adaptation of Divided Wing Sections to Soaring Flight.</u>

With the assumption of an ascending air current, soaring flight may be regarded as gliding flight with increased wind speed. Horizontal soaring flight is possible when the resultant v_s of the wind speed v_w and the gliding speed v_g are both horizontal (Fig. 8). The condition of equilibrium for horizontal soaring flight is

$$\frac{v_w}{v_g} = \frac{\sin \beta}{\sin \epsilon}$$

in which β = angle of incidence of gliding flight.

ϵ = ascending angle of wind.

By substituting the values under the heading B, for the slowest practically possible gliding flight, it is found that the divided wing section requires less wind speed than the closed wing section, provided the ascending wind offsets the value of β of the divided section and the wing loading and fuselage drag are the same in both cases.

For a given wind ascent $\epsilon = 15^\circ$ the following minimum wind strengths are obtained:

a) Section 422

$$v_{w_1} = \frac{v_g \sin \beta}{\sin \epsilon} = 0.499$$

b) Section L-1

$$v_{w_2} = 0.485$$

Hence, with reference to the demand for wind speed, Section L-1 is about 3% more favorable. Both sections are therefore in this respect about equally justified in practice, provided the divided wing section can not be further improved in this direction.

Fig. 1.

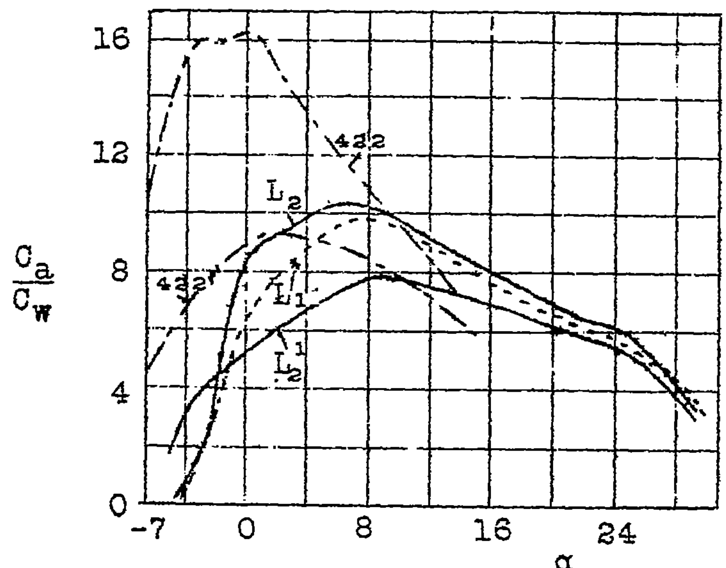


Fig. 4.

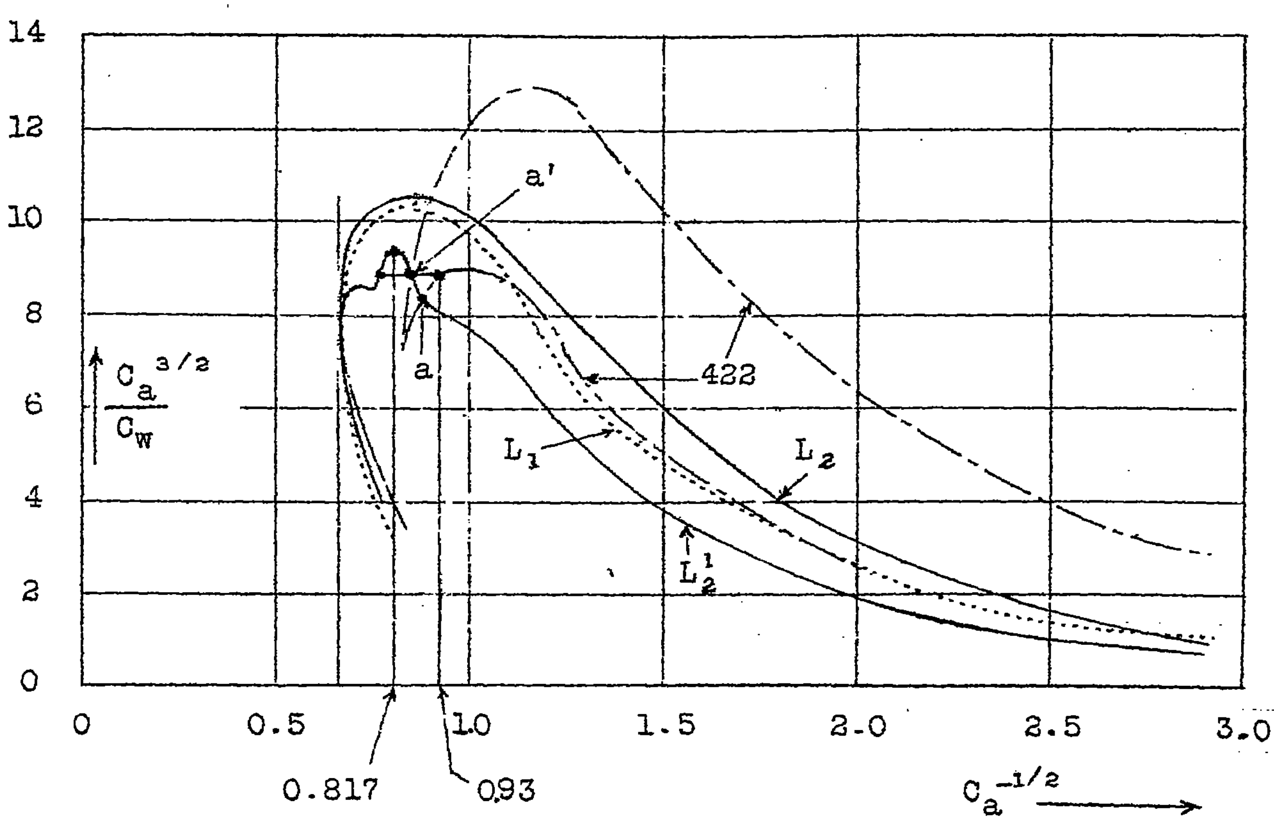


Fig. 5.

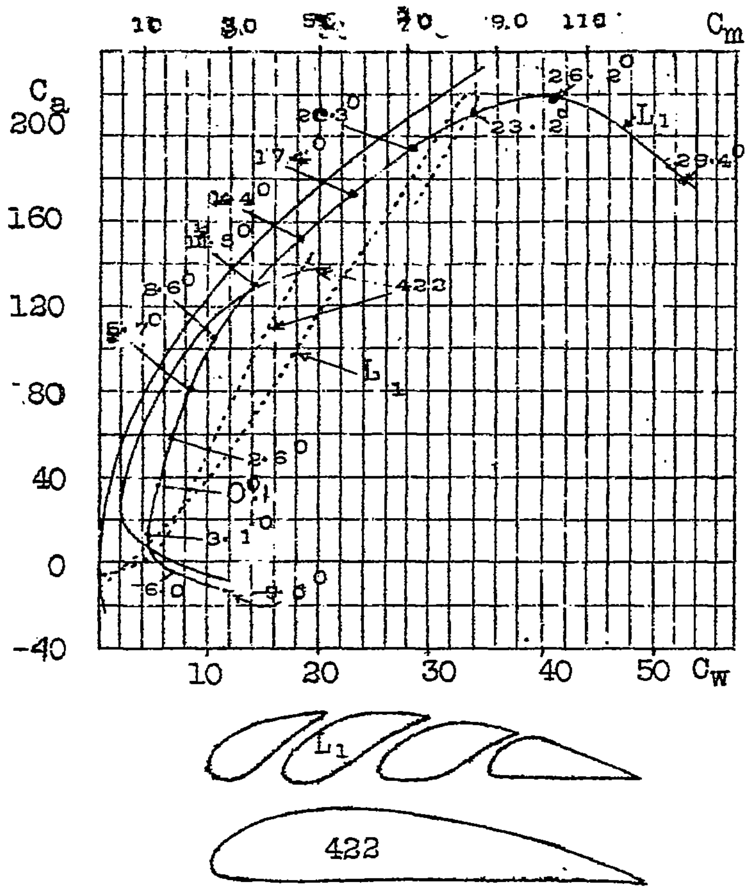


Fig. 2

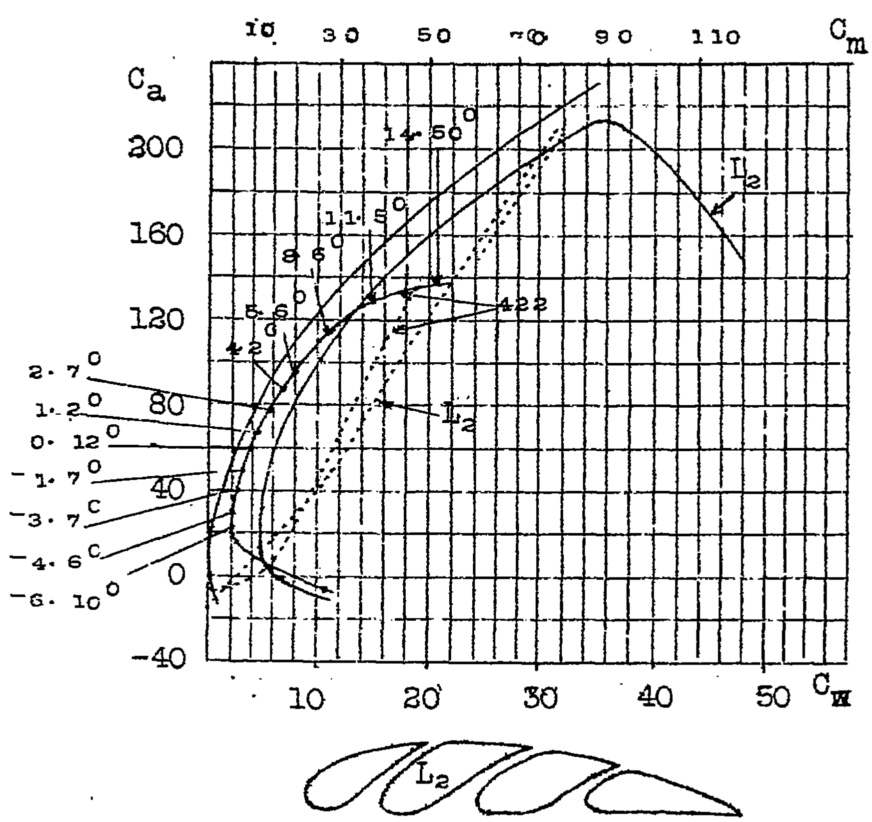


Fig. 3

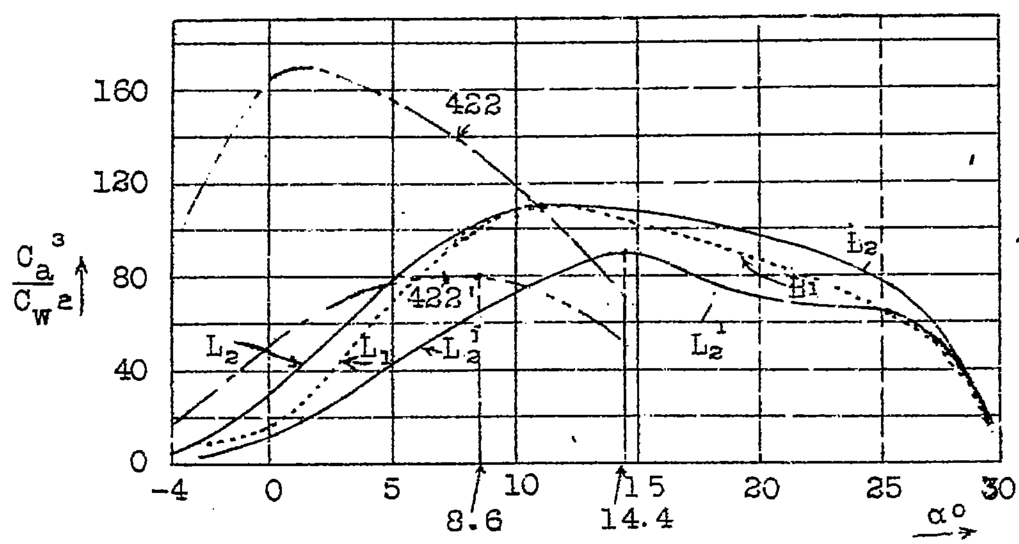


Fig. 6.

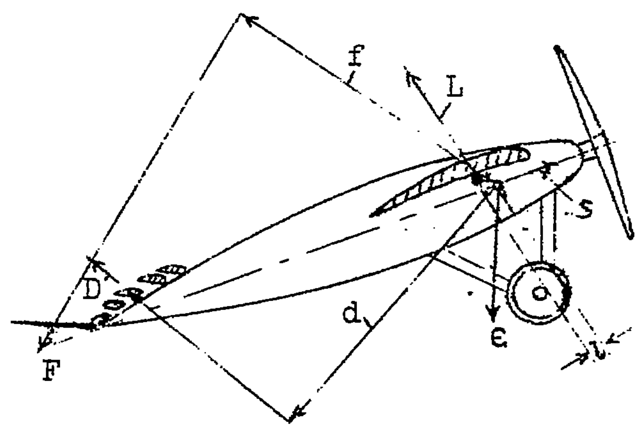


Fig. 7

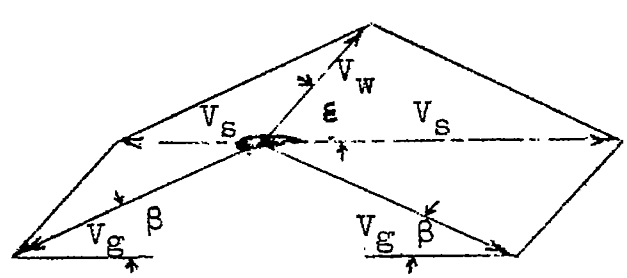


Fig. 8

Göttingen Tests of Handley-Page Wings,

By C. Wieselsberger.

The following preliminary series of twelve experiments was carried out at a wind velocity of 30 meters per second for the purpose of investigating the characteristics of the Handley-Page wings.

1. Testing a wing of the usual Handley-Page shape, so far as the latter is known from the published reports concerning wing No. 1. The experiment shows that the lift increases up to an angle of attack of 27.7°, the maximum lift being here 196.3 (Fig. 1 and Table 1). From the position of the parabola of the induced drag, which is drawn for the aspect ratio of 100.3 : 21.9, it is evident that the wing section drag is not excessive for large angles of attack. On the other hand, for small angles of attack (in the neighborhood of a lift of 40), a strong sudden increase of the wing drag takes place. The wing, therefore, does not show especially favorable characteristics for normal flight, but very favorable, on the contrary, for landing.

2. It was sought to render the sudden increase of drag for small lifts less unfavorable. For this purpose, starting with a previously tested wing section, No. 2a (Fig. 2), the experiment was tried of dividing the section, so as to form a slot for the passage of the air, while retaining the shape (section No. 2). With this slot filled in, wing No. 2 would therefore have exactly the same section as wing No. 2a. The measurements show (Fig. 2 and Tables 2

and 3) a diminution in the suddenness of the drag increase, as was shown for wing No. 1. In other respects the properties were injured for large angles of attack, since on the one hand the drag of the section was increased and on the other hand only a maximum lift of about 160 was attained.

3. The auxiliary wings were tested in three different positions (Fig. 3, wings 3a to 3c). The measurement for 3b, as was to be expected, shows favorable properties for normal flight, while 3c gives a greater lift. Position 3a, which was first tried, is considerably less favorable than 3c. The closing of the slot in the arrangement 3c, as indicated in Fig. 3 (the measurement curve being designated by 3d), gives quite normal results with small and medium lifts. Lifts, drags and moments of curves 3a to 3d, are all given for the sake of better comparison, with reference to the same wing chord of 23 cm. The moment center is the leading edge of the main wing (Figs. 3 and 4 and Tables 4-7).

4. The auxiliary wing, as shown in Fig. 5, was made rotatable, so that the slot between its rear edge and the main wing could be adjusted at different widths. The auxiliary wing rotated about an axis passing through the point D. Four experiments were tried, one with the slot closed and one each with a slot of 1.5, 3, and 5 mm. If the intervening space (with the slot closed) were filled in, we would have the original section No. 387. The polar of this section is drawn with dashes. The results (Figs. 5 and 6 and Tables 8-12) show that the wing with closed slot is decidedly less favorable with reference to drag, than sections 387, from which it

is derived. If the slot is opened by rotating the auxiliary wing more and more, the maximum lift is attained with a slot of 3 mm. The maximum lift is however not so great here as in some arrangements of the first and third series of experiments. The reason for this last phenomenon may, however, under certain circumstances, be due to the less favorable position of the auxiliary wing with reference to the main wing. For calculating the dimensionless coefficients, the chord of the original section (20 cm.) was employed.

It may be seen from the foregoing data that a very high maximum lift can be obtained by utilizing an auxiliary wing in the proper position. On the other hand, there occurred in the field of the angles of attack for normal flight, a strong, sudden increase of drag which could only be eliminated by changing the position of the auxiliary wing or by closing the slot.

Table 1.

Wing 1, section of main wing 398. Span 100.3 cm., chord (including auxiliary wing) 21.9 cm., total surface 2196.6 sq.cm .

Angle of attack.	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-10.0	9.92	1.4	-1.01
-6	- 4.6	6.98	2.7	-0.66
-4.5	3.3	5.56	6.7	0.59
-3.1	14.9	4.29	10.4	3.48
-1.6	24.6	3.73	12.5	6.60
-0.1	33.2	3.58	13.7	9.27
1.4	35.4	3.74	13.8	9.46
2.8	36.7	5.56	12.2	6.59
4.3	38.0	7.45	14.0	5.10
5.8	48.3	7.50	15.7	6.44
8.7	83.6	8.36	23.2	10.0
11.6	111.2	11.4	29.4	9.71
14.5	132.2	15.5	34.0	8.60
17.4	152.2	20.2	38.2	7.54
20.3	169.0	25.3	41.9	6.68
23.3	184.0	30.6	44.5	6.00
25.6	194.0	35.4	47.5	5.48
27.7	196.3	41.4	48.9	4.75
29.2	195.5	45.3	49.6	4.32

Table 2.

Wing 2, Span 99.9 cm., chord (incl. aux. wing) 20.2 cm., total surface 2018 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-6.82	8.40	-1.16	-0.8
-6	-1.57	5.93	2.46	-0.3
-4.5	7.26	4.54	7.8	1.6
-3.1	18.4	3.52	12.3	5.2
-0.1	36.9	3.10	16.8	11.9
2.8	46.4	4.65	18.1	10.0
4.3	49.5	5.61	18.9	8.8
5.8	57.4	6.98	21.5	8.2
8.7	76.0	8.95	26.8	8.5
11.6	98.9	11.3	32.6	8.7
14.6	116.8	14.6	39.5	8.0
17.5	131.3	19.0	44.0	6.9
20.5	143.0	23.6	47.9	6.1
23.4	152.0	27.6	50.0	5.5
26.2	158.5	33.8	53.6	4.7
29.5	146.8	46.2	56.5	3.2

Table 3.

Wing 2a, section No. 404, Span 100 cm., chord 20 cm., total surface 2000 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-8.9°	-16.2	8.75	-1.3	-1.8
-6.0	2.0	4.06	7.6	0.5
-4.5	12.4	1.85	11.0	6.7
-3.1	23.4	1.83	13.1	11.9
-1.6	32.7	2.22	15.6	14.8
-0.2	42.2	2.65	17.7	15.9
1.3	54.9	3.31	20.8	16.5
2.8	63.3	3.88	23.2	16.3
4.2	73.8	4.95	25.7	14.9
5.7	83.8	6.06	28.2	13.8
8.6	103.3	8.60	33.5	12.0
11.6	119.2	11.8	36.8	10.1
14.5	131.4	15.2	38.8	8.6
17.5	136.9	20.3	43.0	6.6

Table 4.

Wing 3a, Span 100.1 cm., chord (incl. aux. wing) 23.7 cm. (calculation chord 23), calculation surface 2302 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-8.9°	-16.0	11.9	0.7	-1.3
-6	- 5.78	8.51	4.4	-0.7
-3.1	15.5	6.14	10.4	2.5
-0.1	29.0	7.56	13.5	3.8
2.9	29.6	10.0	14.0	3.0
5.8	57.0	9.39	21.5	5.1
8.7	82.0	10.6	26.8	7.7
11.6	101.8	13.0	30.0	7.8
14.5	118.6	16.1	32.6	7.3
17.5	129.1	20.9	34.5	6.2
20.4	135.5	25.0	35.1	5.4
23.4	144.6	28.7	35.4	5.0
25.8	147.0	31.6	35.4	3.2
29.3	158.0	37.7	38.0	4.2
32.3	169.0	43.6	40.2	3.9
35.3	164.0	48.5	40.2	3.4

Table 5.

Wing 3b, Span of main wing 100.1 cm., chord 20 cm. (calculation chord 23 cm.), calculation surface 2302 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-4.2	6.45	2.6	-0.7
-6.1	13.2	2.40	8.7	5.5
-3.1	32.8	2.74	11.9	11.7
-0.2	51.4	3.77	15.5	13.6
2.7	70.6	5.41	19.9	13.1
5.6	89.1	7.75	24.6	11.5
8.5	109.8	10.7	28.9	10.3
11.5	127.0	14.6	33.4	8.7
14.6	141.0	19.1	37.6	7.4
17.4	149.2	23.7	38.9	6.3
20.5	126.0	36.6	39.2	3.4

Table 6.

Wing 3c, Span 100.1 cm. chord (incl. aux. wing) 23 cm. (calculation chord 23 cm.), total surface 2302 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-5.37	9.25	2.5	-0.58
-6	0.8	6.50	5.8	0.12
-4.5	9.3	4.97	9.5	1.87
-3.1	20.5	3.91	12.8	5.25
-1.6	30.0	3.48	14.2	8.62
-0.2	36.7	3.63	14.7	10.1
2.8	38.9	5.19	13.6	7.5
5.7	66.5	6.20	18.2	10.7
8.6	94.4	8.97	23.4	10.5
11.5	118.3	12.7	27.5	10.1
14.4	138.8	17.1	31.0	8.13
17.3	157.5	22.1	34.8	7.13
20.3	174.0	27.2	37.5	6.40
23.2	185.0	32.4	39.1	5.71
25.7	195.3	37.4	40.9	5.22
27.3	169.0	40.0	38.1	4.23
29.4	134.4	41.1	33.4	3.27

Table 7.

Wing 3d. Arrangement the same as for wing 3c, but with closed slot. Span 100.1 cm., chord (incl. aux. wing) 23 cm., total surface 2302 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-5.92	9.00	2.9	-0.66
-6	2.57	6.01	6.6	0.43
-3.1	22.2	3.56	13.2	6.24
-0.2	40.7	3.24	15.2	12.6
2.8	59.3	4.40	17.2	13.5
5.7	73.9	6.36	18.5	11.9
8.6	91.0	9.25	20.3	9.8
11.5	107.3	12.8	23.0	8.4
14.5	127.5	17.0	25.1	7.5
17.4	142.6	21.2	28.1	6.7
20.4	142.0	27.8	30.3	5.1

Table 8.

Wing 4, Slot 0 mm., Span 99.8 cm., (calculation chord 20 cm.) calculation surface 1996 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-4.3	8.02	2.4	-0.5
-6	7.2	4.36	9.8	1.6
-3.1	27.4	2.60	14.1	10.6
-0.2	45.7	3.24	16.9	14.1
2.8	63.4	4.60	19.2	13.8
5.7	80.5	6.77	22.0	11.9
8.6	97.6	9.34	24.6	10.4
11.6	119.8	12.4	28.5	9.6
14.5	131.2	16.3	31.1	8.1
17.5	135.8	21.2	33.0	6.4
20.5	135.8	26.2	34.4	5.2
23.7	87.9	39.2	30.2	2.2

Table 9.

Wing 4, Slot 1.5 mm., Span 99.8 cm., (calculation chord 20 cm.), calculation surface 1996 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-8.0	8.25	1.7	-1.0
-6	6.7	4.50	9.3	1.5
-3.1	26.1	2.81	13.3	9.3
-0.1	37.3	3.56	14.2	10.5
2.8	44.4	6.35	16.1	7.0
5.8	64.9	7.02	18.9	9.2
8.7	88.0	9.00	23.1	9.7
11.6	107.5	12.1	26.9	8.9
14.5	126.0	15.8	31.2	8.0
17.5	145.0	19.7	34.8	7.4
20.4	157.9	25.0	38.5	6.3
23.4	166.4	31.1	41.3	5.4
25.6	169.3	34.8	42.5	4.9
29.7	90.6	47.1	32.8	1.9

Table 10.

Wing 4, Slot 3 mm., Span 99.8 cm., (calculation chord 20 cm.), calculation surface 1996 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment. Coefficient C_m	L/D (A/W)
-9°	-11.2	8.39	1.7	-1.3
-6	7.0	4.33	9.4	1.6
-3.1	24.8	3.03	12.8	8.2
-0.1	28.8	5.11	12.7	5.6
2.9	34.8	8.46	15.4	4.1
5.8	66.2	6.96	19.6	9.5
8.7	91.4	9.01	24.5	10.1
11.6	113.9	12.2	29.4	9.3
14.5	137.0	16.3	34.6	8.4
17.4	151.1	20.5	37.6	7.4
20.4	164.5	25.6	41.5	6.4
23.4	173.6	32.3	44.7	5.4
25.6	176.9	36.6	47.6	4.8
29.5	143.0	47.6	43.8	3.0

Table 11.

Wing 4, Slot 5 mm., Span 99.8 cm. (calculation chord 20 cm.), calculation surface 1996 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-12.9	8.50	1.9	-1.5
-6	5.0	5.15	8.5	1.0
-3.1	23.3	3.71	11.8	6.3
-0.1	29.1	6.95	14.1	4.2
2.9	31.6	10.8	16.2	2.9
5.8	51.7	9.75	18.9	5.3
8.7	76.5	10.8	24.2	7.1
11.6	96.4	14.4	29.0	6.7
14.6	113.0	18.2	33.1	6.2
17.5	126.1	23.0	36.3	5.5
20.5	138.0	27.8	39.8	5.0
23.5	148.5	32.3	42.2	4.6
25.6	155.0	36.0	44.5	4.7
29.4	160.0	43.1	49.2	3.7

Table 12.

Wing section 387, Span 100 cm., chord 20 cm., total surface 2000 sq.cm.

Angle of Attack	Lift Coefficient C_a	Drag Coefficient C_w	Moment Coefficient C_m	L/D (A/W)
-9°	-10.4	6.90	5.3	-1.5
-6	8.2	1.80	12.3	4.5
-4.6	18.2	1.79	14.6	10.1
-3.1	28.0	2.01	16.7	13.9
-1.6	38.0	2.35	19.2	16.1
-0.2	46.8	2.91	21.8	16.4
1.3	58.1	3.57	24.2	16.3
2.7	68.1	4.38	26.5	15.5
4.2	78.9	5.31	28.8	14.8
5.7	87.2	6.31	31.0	13.7
8.6	108.5	9.21	37.5	11.8
11.6	121.8	12.4	41.0	9.9
14.5	134.0	16.2	42.9	8.3
17.5	136.0	21.7	45.2	6.3

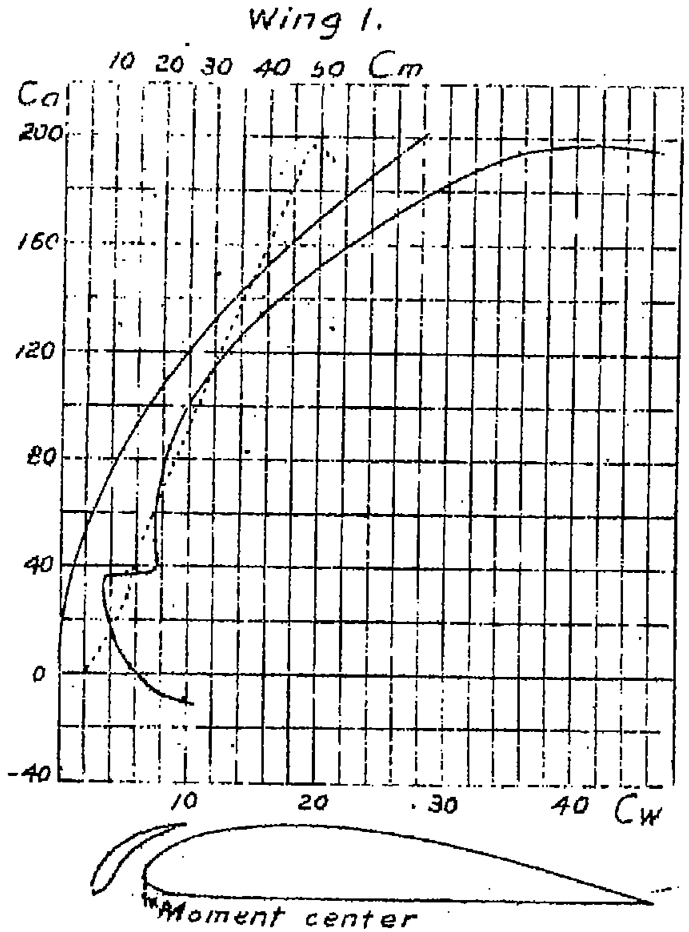

Wing 1.
10 20 30 40 50 Cm
Ca
200
160
120
80
40
0
-40
10
20
30
40
Cw
Moment center

Fig. 1.

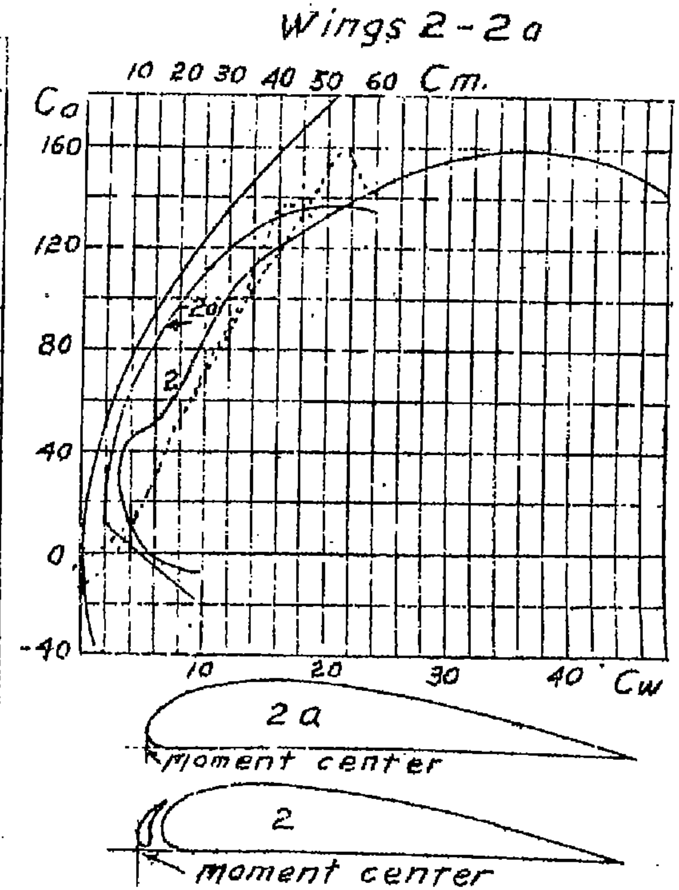

Wings 2 - 2a
10 20 30 40 50 60 Cm.
Ca
160
120
80
40
0
-40
2a
2
10
20
30
40
Cw
2a
moment center
2
moment center

Fig. 2.

Wings 3a to 3d

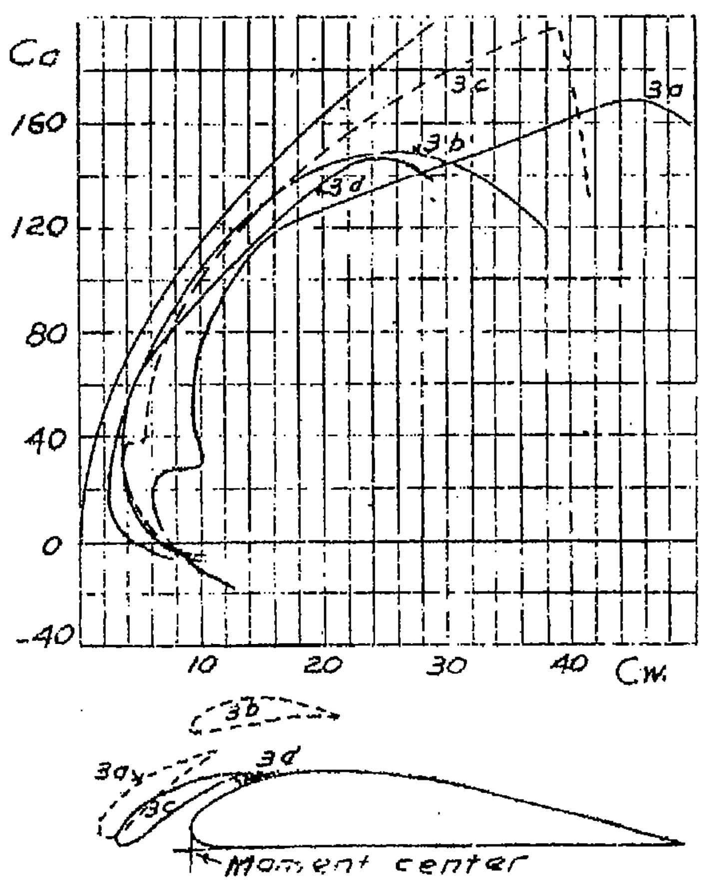
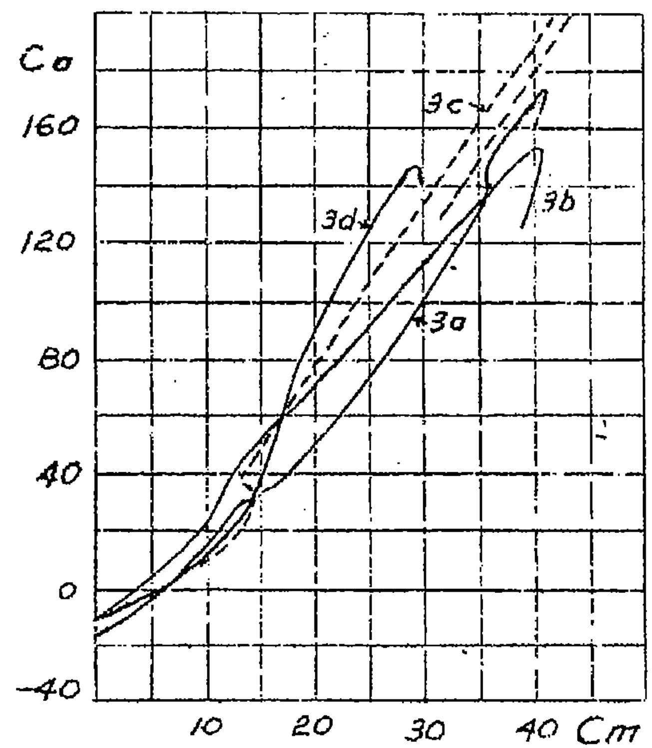


Fig. 3.



Moment curves of wings 3a to 3d.

Fig. 4.

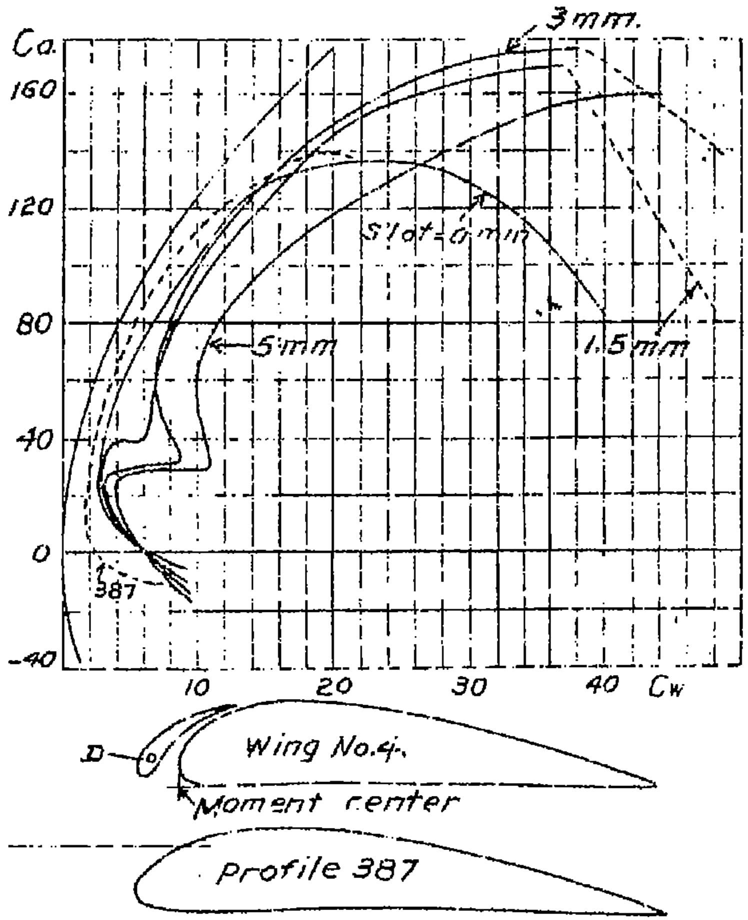

Ca.
3 mm.
160
120
Slot=0 mm
80
5 mm
1.5 mm
40
0
387
-40
10
20
30
40
Cw
D
Wing No.4.
Moment center
Profile 387

Fig. 5.

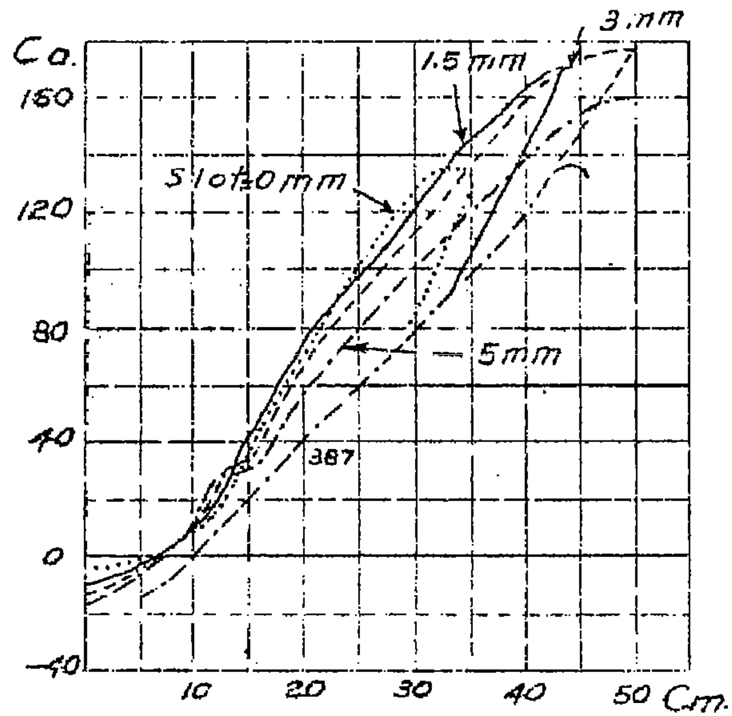

Ca.
3 mm
1.5 mm
160
Slot=0 mm
120
80
5 mm
40
387
0
-40
10
20
30
40
50 Cm.

Fig. 5.

Experiments with Slotted Wings,

By R. Katzmayr and L. Kirste of Vienna.

About a year ago there appeared the first announcement of a new wing, made by the English firm of Handley-Page, which was claimed to have considerably greater lift for a given speed. On account of the paucity of information, an arrangement like Fig. 1 was first tested, that is, a narrow auxiliary wing was added in front of the regular wing so as to leave a slot. Later experiments were tried with two such wings (Fig. 2) and finally with the whole wing divided like a window shutter (Fig. 3). The experiments were performed partly in the wind tunnel and partly on an airplane. The results showed that an increase in lift up to 60% could be obtained with one auxiliary wing and corresponding multiples with two or more.

The theoretical foundation for such a lift increase had already been sought in various ways (Luftfahrt 1920, p.175). According to one theory, the slot behind the auxiliary wing increases the vacuum over the front part of the wing, as the result of a sort of "Venturi action." According to another theory, the region of strongly diminished pressure is extended further back.

In order to verify the previously published data and also obtain a general view of the phenomena produced by divided wings, two series of experiments were carried out in the aerodynamical laboratory of the Technical High School in Vienna.

First a normal shaped wing which was on hand, 900 x 150 mm. (Fig. 4), was tested in the wind tunnel. The experiments were performed under a pressure of 20 mm. of water (2 grams per square centimeter) and included angles of attack from 0° to 27°. The lift and drag were measured and also, for corroboration, the lift-drag ratio for each 3° change in the angle of attack. So far as convenient and especially for the larger angles, the measurements were made for each degree. In the illustrations are given the measurements reduced to "unit values." The surface F of the wing model employed as the base for calculating these unit values ($^cA = A/F \times p$ and $^cW = W/F \times p$)* was obtained from the product of the span and total wing chord, without reference to the slots.

The original wing was first subjected to the air current in the wind tunnel and then the cuts shown in Fig. 4 were made with a circular saw and the wing was again subjected to the air current. The cuts extended clear through the section from the top to the bottom, narrow connections being left only on the edges of the wing and in about 1/3 of the span. The slots will be designated as a, b, c. Slots a and c were of equal width (1.8 mm.), and slot b was 2.5 mm. wide. Slot a was afterwards widened on the lower side of the wing, so that its cross-section was wedge-shaped, as shown in Fig. 4. The inlet and exit openings of the slots are parallel to the leading edge of the wing. All the variations of the three slots were tested, up to the combinations of d with b and c

* The Austrian designations ^cA and ^cW are equivalent to the German C_a and C_w. [p is the impact pressure. Tr.]

The comparative values of the polars, reproduced in Figs. 5 and 6, are given in Table 1.

Table 1.

α°	Original Wing			Wing with Slot: c		
	$1000 \times c_A$	$100 \times c_W$	$1000\ \epsilon$	$100 \times c_A$	$100 \times c_W$	$1000\ \epsilon$
0	17.8	2.44	132	17.4	2.44	140
3	34.4	2.48	72	34.8	2.56	73.5
6	53.6	3.44	64	54.8	3.63	66.5
9	73.0	5.22	71.5	75.5	5.55	73.5
12	92.5	7.89	85	94.7	8.11	85.5
15	107.7	12.2	113	111.0	12.2	109
18	112.0	18.0	161	116.7	18.1	155
21	114.3	24.2	222	118.1	24.5	207
22	114.8	--	--	118.1	26.8	227
23	114.3	--	--	--	--	--

If slot a is open, there occurs a considerable diminution of the lift values, with a simultaneous increase of the corresponding drags. For slot b alone, there is a simultaneous diminution of both lift and drag, although of considerably less amount. The effect of slot c alone is, on the other hand, favorable, for the lift values are greater than for the original wing, while the drag remains unchanged. The lift increase is already evident for small angles of attack, but is relatively greater from 12° on.

Combinations of two of the three slots gave the following results:

1. For a and b, decrease in both lift and drag;
2. The same for a and c, but in greater degree.
3. For b and c, there was first a very strong increase in drag for angles of attack below 12°, with simultaneous decrease

of the corresponding lift values, while above 18° the lift constantly increased in comparison with that of the original wing. This phenomenon is due to the favorable effect of slot c. It may be further gathered from the diagrams that the values for the pairs of slots can be obtained from the values for the single slots by addition, and that consequently the slots exert no mutual influence on one another. This also holds true when all three slots are open, as shown in Fig. 6.

The effect of the wedge or nozzle-shaped slot d is of interest in so far as the lift values for an angle of attack of about 8° show improvement in comparison with the values for the parallel-sided slot a, without however attaining the values for the middle slot b.

For answering the question as to how the slots affect the distribution of the pressure on the wing, the static pressure on the upper side of the wing was measured, for different angles of attack, in the middle of the span, at five points of the wing section marked in Figs. 7a and 7b. The results are reproduced in Fig. 7a for the original wing, and in Fig. 7b for the wing with slot c. It is accordingly evident that, with the conduction of the excess pressure to the top of the wing, especially for large angles of attack, an increase of the partial vacuum occurs over the rear half of the wing and the pressure on the bottom is only slightly diminished.

A second series of experiments was instituted with a wing combination whose section is reproduced in Fig. 1. The auxiliary wing is attached to the main wing by five steel rods. By moving the auxiliary wing on these rods, the distance a was varied between 8 and 40 mm. It was again subjected to the air current at p = 20 mm. water pressure. Comparative experiments at p = 30 and 40 mm. exhibited only the usual decrease of the unit drag. A disturbance of the air current by means of a net with 5-cm. meshes exerted no particular influence. As the surface for the calculation of the unit values, the product of the span by the sum of both wing chords ($F = 0.900\ (0.150 + 0.0296) = 0.1617$ sq.m.) was taken.

<u>Table 2</u>.

α°	α = 0 mm.			α = 28 mm.		
	1000 x c_A	100 x c_W	1000 ϵ	100 x c_A	100 x c_W	1000 ϵ
0	14.6	1.55	106	10.2	3.6	--
3	31.4	2.01	64	23.8	4.6	194
6	48.9	2.94	60	39.6	5.6	141
9	65	4.65	72	57	6.5	114
12	81	7.0	86	79	8.4	106
15	94	9.6	102	99	10.8	110
18	103	14.2	139	117	14.8	126
19	104	16.3	157	--	--	--
20	97 85	21.7	224 355	--	--	--
21	84	23.2	276	131	19.5	150
24	76	26.8	--	144	25.3	176
27	70	--	--	152	31.3	206
30	63	--	--	157 117	38.4	245 330
33	--	--	--	117	44.8	380

The greatest increase in the maximum lift took place with a = 28 mm., as shown by Fig. 8. For this case and for the wing alone, Fig. 9 gives the two polars, and Table 2 gives the corresponding values. It is evident that the lift diminishes for small angles of attack and first shows a definite gain above 12°. The lift-drag ratios are considerably poorer for all positions of the auxiliary wing, as shown in Fig. 8.

In order to answer the question as to how the lift is increased, the pressure distribution was measured, as in the first series of experiments, for the wing alone and for the position a = 28 mm., according to Figs. 10a and 10b. A further extension of the diminished pressure region toward the rear was not noticeable, but only an increase on the fore part of the wing.

As the final result of both series of experiments, the influence of the "auxiliary wing" is quite different from that of the slot, as is evident from a comparison of the diagrams. Both methods improve the lift values, but the auxiliary wing does so to a far greater degree. While the latter seriously decreases the lift-drag ratio, a slot c near the trailing edge, somewhat improves it.

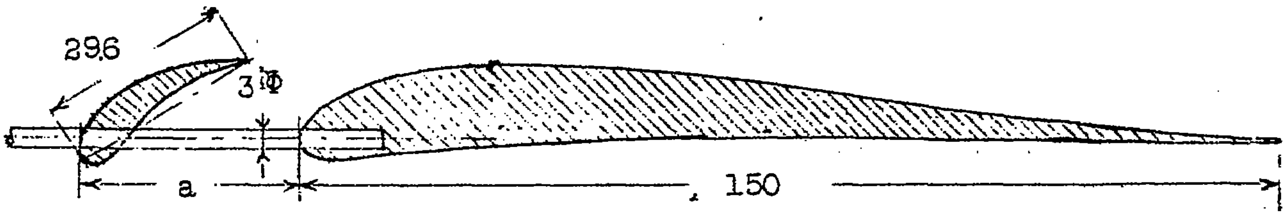


Fig. 1.

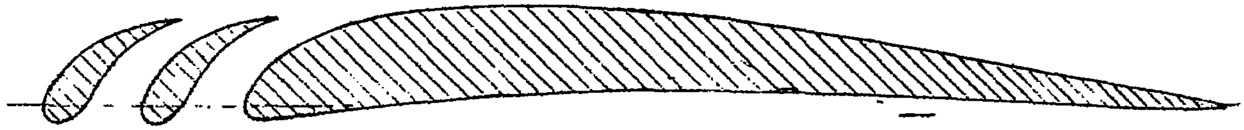


Fig. 2.

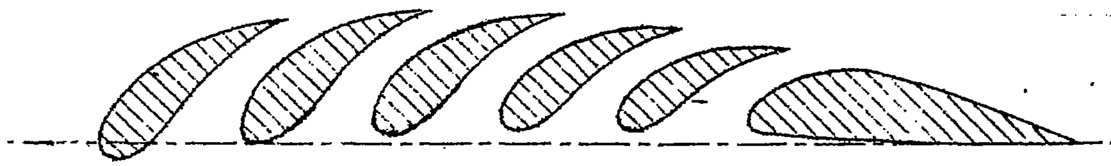


Fig. 3.

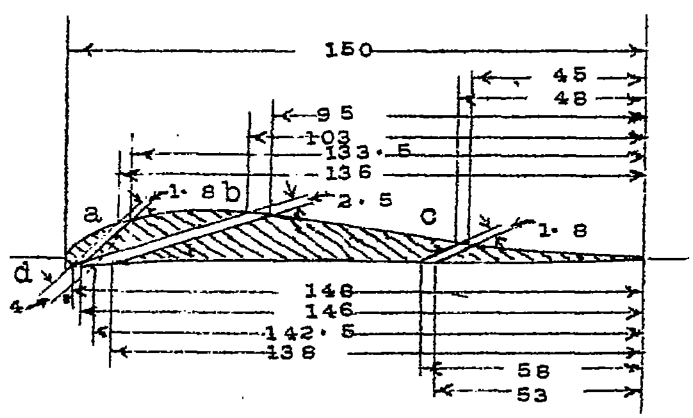


Fig. 4.

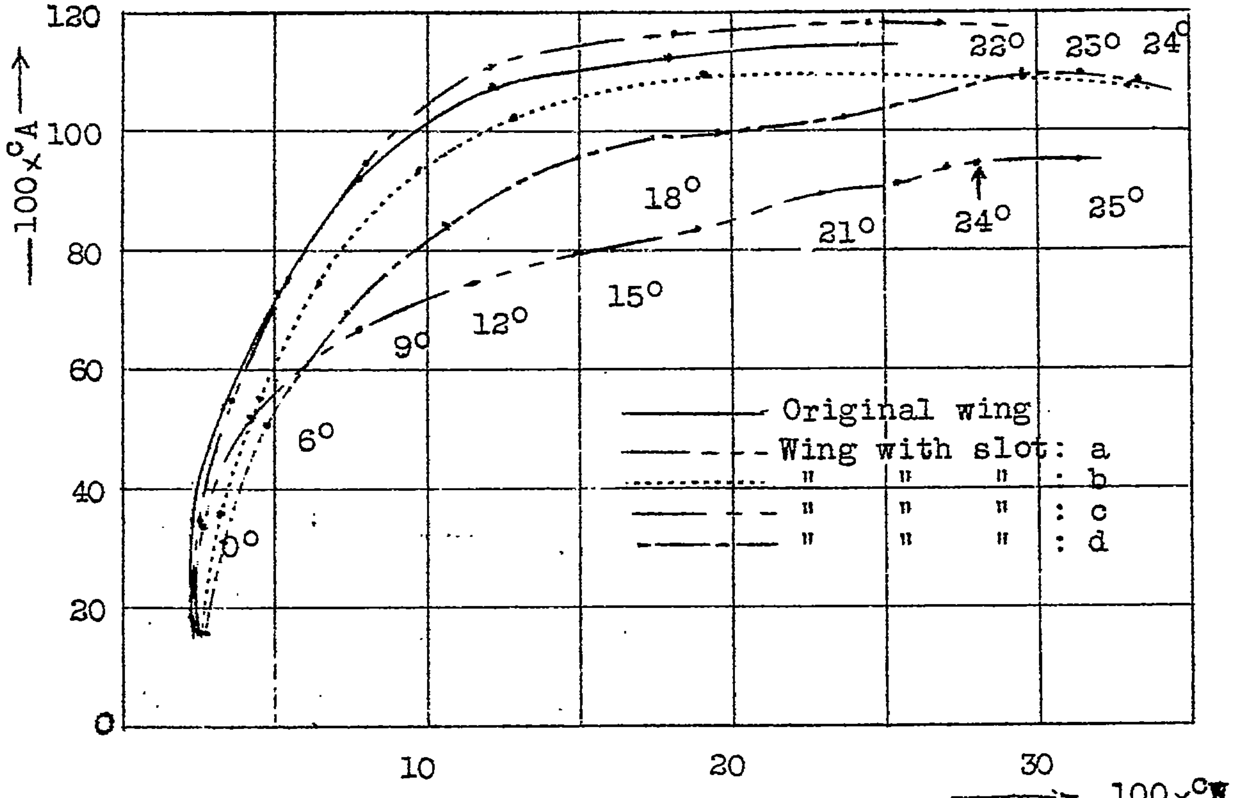

120
100
80
60
40
20
0
$100 \times c_A$
10
20
30
$100 \times c_W$
0°
6°
9°
12°
15°
18°
21°
24°
25°
22°
23°
24°
Original wing
Wing with slot: a
" " " : b
" " " : c
" " " : d

Fig. 5.

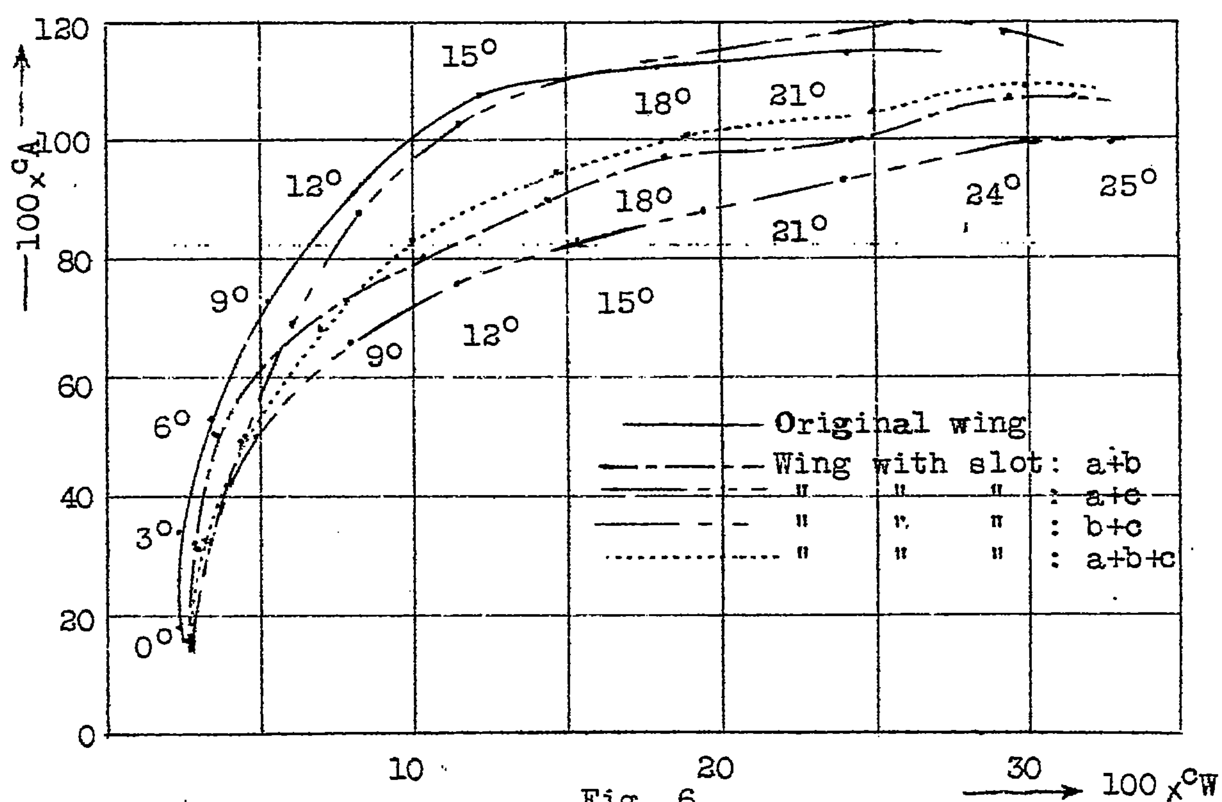

120
100
80
60
40
20
0
$100 \times c_A$
10
20
30
$100 \times c_W$
0°
3°
6°
9°
12°
15°
18°
21°
9°
12°
15°
18°
21°
24°
25°
Original wing
Wing with slot: a+b
" " " : a+c
" " " : b+c
" " " : a+b+c

Fig. 6.

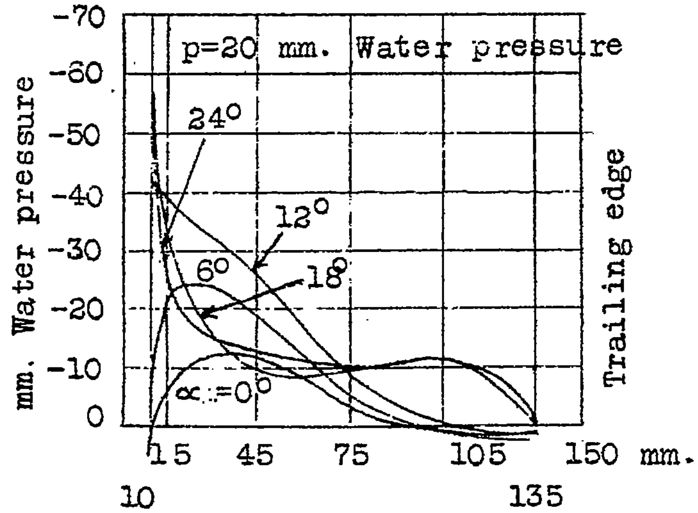


Fig. 7a.

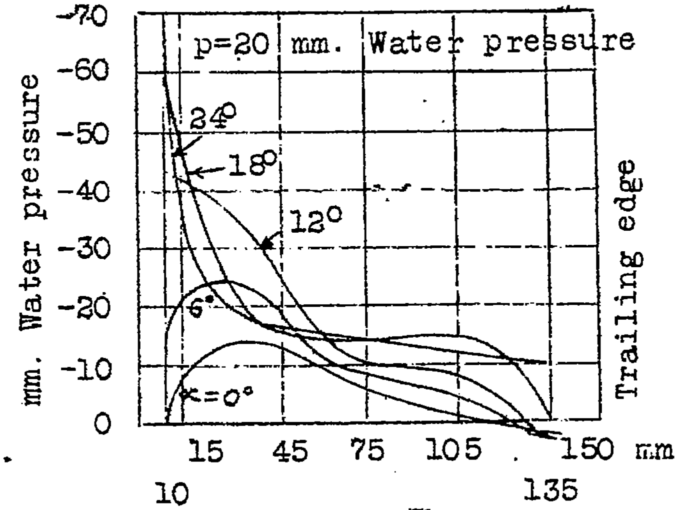


Fig. 7b.

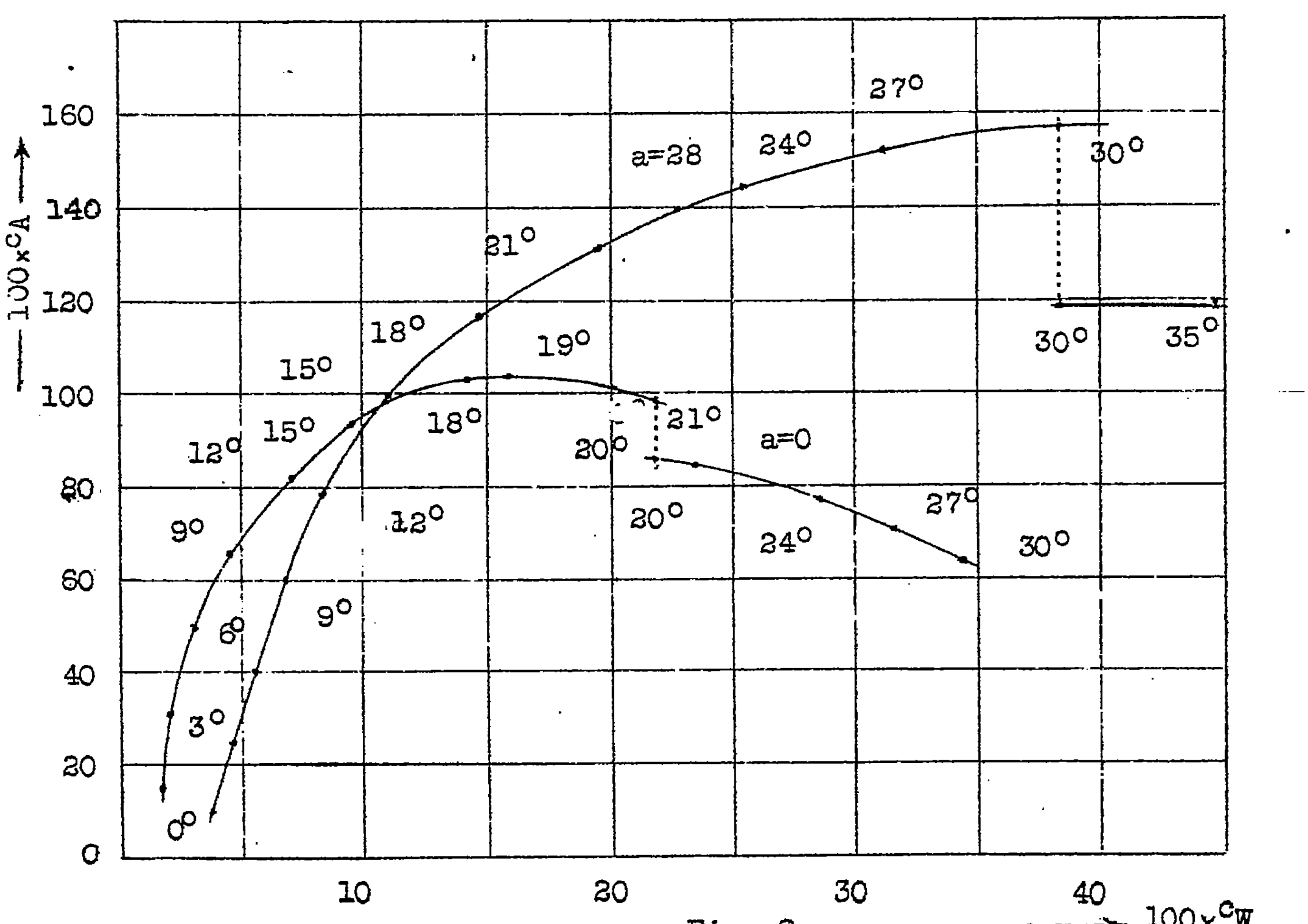


Fig. 9.

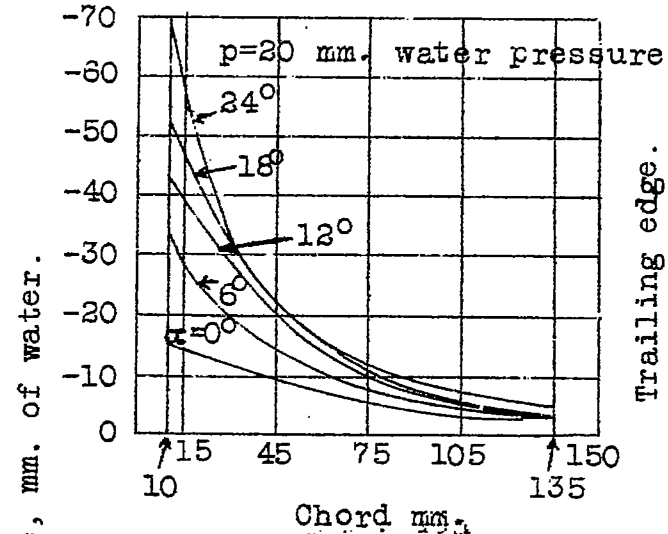


Fig. 10a.

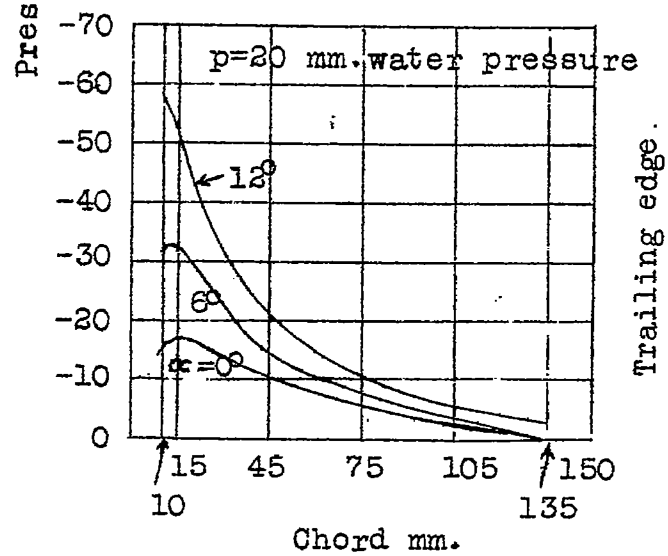


Fig. 10b.

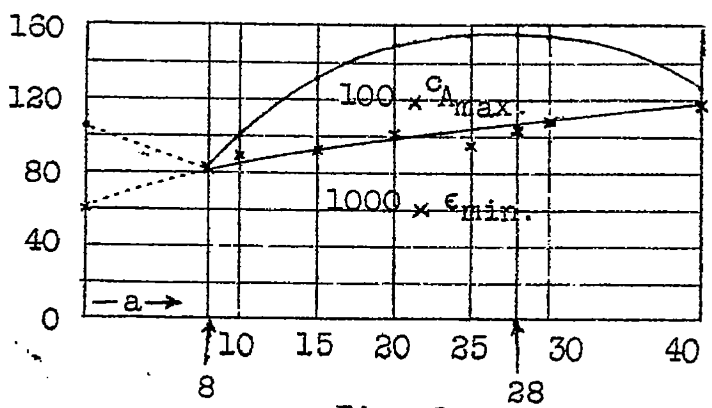


Fig. 8